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Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas

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Abstract

Topography, vegetation, and climate act together to determine the spatial patterns of fires at landscape scales. Knowledge of landscape-fire-climate relations at these broad scales (1,000s ha to 100,000s ha) is limited and is largely based on inferences and extrapolations from fire histories reconstructed from finer scales. In this study, we used long time series of fire perimeter data (fire atlases) and data for topography, vegetation, and climate to evaluate relationships between large 20th century fires and landscape characteristics in two contrasting areas: the 486,673-ha Gila/Aldo Leopold Wilderness Complex (GALWC) in New Mexico, USA, and the 785,090-ha Selway-Bitterroot Wilderness Complex (SBWC) in Idaho and Montana, USA. There were important similarities and differences in gradients of topography, vegetation, and climate for areas with different fire frequencies, both within and between study areas. These unique and general relationships, when compared between study areas, highlight important characteristics of fire regimes in the Northern and Southern Rocky Mountains of the Western United States. Results suggest that amount and horizontal continuity of herbaceous fuels limit the frequency and spread of surface fires in the GALWC, while the moisture status of large fuels and crown fuels limits the frequency of moderate-to-high severity fires in the SBWC. These empirically described spatial and temporal relationships between fire, landscape attributes, and climate increase understanding of interactions among broad-scale ecosystem processes. Results also provide a historical baseline for fire management planning over broad spatial and temporal scales in each wilderness complex.

Introduction

Fire frequency, along with fire severity and size, affects the composition, structure, and successional trajectories of Rocky Mountain forests in the Western United States (Habeck and Mutch 1973; Arno 1980; Romme and Knight 1981; Romme 1982; Johnson 1992; Agee 1993; Turner et al. 1997). At fine spatial and temporal scales (individual trees and forest stands, seconds to hours), the physics of fire spread are well known (Albini 1976; Rothermel 1983). The climatic and anthropogenic constraints on fire occurrence have also been documented in many studies conducted at much broader scales (regions, centuries, and millennia; Barrett and Arno (1982) and Gruell (1985), Baisan and Swetnam (1990), Swetnam (1993), Barrett et al. (1997), Swetnam and Betancourt (1998)). Few studies, however, have empirically determined the factors that determine the variability of fire patterns at intermediate spatial and temporal scales: 1,000s to 100,000s of ha, and over the decades of the 20th century (but see Chou et al. (1990) and Barton (1994), McKelvey and Busse (1996), Kushla and Ripple (1997), Heyerdahl et al. (2001)). Understanding temporal and spatial constraints on fire frequency at these intermediate scales is important for both fire and vegetation management and for increasing the understanding of how landscape patterns influence fire processes and vice versa.

Centennial to seasonal climate variability entrains fire regimes (Swetnam and Betancourt 1998; Veblen et al. 1999; Grissino-Mayer and Swetnam 2000). Drought directly affects fire occurrence by determining fuel moisture and by constraining productivity (Schroeder and Buck 1970; Agee 1993). Anthropogenic ignitions locally affected fire frequencies in the United States prior to European settlement (Gruell 1985; Boyd 1999); and fire suppression and land-use patterns have dramatically affected twentieth-century fire frequencies (Minnich 1983; Covington et al. 1994; Swetnam and Baisan 1996; Rollins et al. 2001). While the temporal patterning of fire is important for evaluating the effects of changing fire regimes, this paper focuses on factors that influence the spatial patterning of fire frequency across landscapes.

Quantitative understanding of the interactions between landscape patterns and ecosystem processes is a main focus of landscape ecology and is necessary for managing landscapes with an ecosystem perspective (Turner et al. 1995; Christensen et al. 1996). The scarcity of research into the influence of landscape patterns on fire processes limits understanding of the effects of changing fire regimes and how landscapes will respond to these changes. Lack of knowledge of fire-landscape-climate interactions also hinders efforts to assess long-term consequences of ecologically based fire management strategies that involve both wildland fire use and wildfire suppression (Kaufmann et al. 1994; Jensen and Bourgeron 1993). The increasing demand for information on the frequency of fire in wilderness and other areas is a direct consequence of fire management strategies focused on 1) assessing broad-scale fire hazard, 2) restoring fire to its natural role in ecosystems, and 3) strategic fire suppression planning. Knowledge of the factors that determine landscape-scale spatial and temporal fire patterning is critical for 1) predicting fire effects under changing climate, 2) mapping departures from pre-20th century fire regimes, 3) planning the restoration of fire as an ecosystem process, and 4) mitigating potentially hazardous fire conditions at broad scales.

Several direct and indirect environmental gradients act together to constrain fire patterns in time and space. Topography influences fire occurrence, behavior, and effects at landscape to regional scales (Agee 1993). Temperature and water availability change with elevation, contributing to shifts in vegetation and different seasonal fuel moistures (Whittaker and Niering 1965; Stephenson 1990). Mountain ranges affect large air masses via orographic lifting, which increases precipitation, changes the timing and severity of storms, and contributes to the potential for ignition of fires by lightning (Schroeder and Buck 1970; Fuquay et al. 1979). Slope angles affect fire spread by increasing the efficiency of radiant energy transfer from flaming fronts to upslope fuels (Albini 1976; Rothermel 1983; Agee 1993). Aspect affects fuel moisture status by determining insolation (Frank and Lee 1966; Waring and Running 1998). Steep, southwest-facing aspects tend to have the highest irradiance and driest conditions; however, lack of sufficient fuels on these slopes because of low productivity may limit fire ignition and spread. Northeast aspects are more productive than other aspects in general, and in fuel-limited ecosystems may have the fuel continuity necessary for fire spread (Agee 1993).

Fires are most frequent at elevations where neither fuel continuity nor moisture is limiting (Martin's 1982). According to this theoretical model of the spatial distribution of fire frequency, middle elevations support frequent fires because sites are sufficiently productive (fuels are continuous) and dry (ignition potential is high and flaming fronts spread readily) to allow fire spread. In general, lower and upper elevation sites have lower productivity and moist conditions, respectively. This reduces ignition probability and the likelihood of fire spread (Martin's 1982; Barton 1994). Here we use Martin's (1982) theoretical model of fire frequency to formulate hypotheses. We also extend it to other landscape gradients (e.g. slope and aspect) that control horizontal fuel continuity and moisture status.

To evaluate relationships between fire regime, landscape characteristics, and climate we analyzed 20th century time series of fire perimeter data (fire atlases) along topographic, biophysical, and climatic gradients in the 486,673-ha Gila Aldo Leopold Wilderness Complex (GALWC) in New Mexico, USA and the 785,090-ha Selway-Bitterroot Wilderness Complex (SBWC) in Idaho and Montana, USA. Our objectives were to determine how probabilities for areas to burn multiple times are related to topography, vegetation, and climate using spatially and temporally continuous data for fire occurrence, topography, potential vegetation type, and climate. In a separate paper we focus on assessing the amount and rate of burning over time in our study areas (Rollins et al. 2001). Comparative analyses both within and between these dramatically different wilderness complexes provide opportunities to both generalize our findings and allow identification of specific, unique relationships between landscape factors and the probability of an area to burn multiple times, thereby strengthening inferences about how landscape patterns influence fire processes. It is important to note that we use the term fire frequency to describe the number of times a specific area (in this case, a pixel or grid cell) burned during the period of record for the fire atlas from each wilderness complex.

We expect that landscape-scale patterns of fire frequency will be related to aspect, slope, elevation, and potential vegetation type. Steeper slopes and slopes that receive higher insolation will tend to have relatively high fire frequencies. Functional processes behind these relationships will be related to both horizontal fuel continuity and local fuel moisture status. We hypothesize that years with the most extensive fires will be dry, preceded by moist years similar to results from Swetnam and Betancourt (1990) and Veblen et al. (1999), Grissino-Mayer and Swetnam (2000).

Study areas

Gila/Aldo Leopold Wilderness Complex

The 486,673-ha Gila/Aldo Leopold Wilderness Complex (Figure 1) encompasses the headwaters of the Gila River, the Mogollon Mountains, and the Black Range 70 km north of Silver City, New Mexico, USA, and is mostly contained within the Gila National Forest and the Gila Cliff Dwellings National Monument. Elevations range from 1,300 m near the main stem of the Gila River to 3,300 m on top of the Mogollon Mountains. The Aldo Leopold Wilderness portion is rugged, with elevations ranging from 1,500 m near the Mimbres River to 2,900 m on McKnight Mountain in the Black Range. Parent material of the GALWC results from volcanic events in the late Cretaceous (USGS 1965). The Gila Conglomerate, a tertiary sedimentary formation, is exposed in tall, pinnacle-like rock formations along the Middle and East Forks of the Gila River.

Average annual precipitation in the GALWC varies from 250 mm in the valleys to 760 mm in the mountain ranges (Beschta 1976). Precipitation over the year is bi-modal, with a wet period from December to March, and monsoonal storms from the Gulf of Mexico occurring between July and September. Mean daily temperatures vary from below freezing in the winter to extremely hot in the mid-summer (30 °C). Spring conditions are usually dry with thunderstorm activity increasing in early July. Thunderstorms occur nearly daily during summer months, resulting from rapid lifting of moist air masses from the Gulf of Mexico. The GALWC has perhaps the highest level of lightning-caused fire occurrence in the nation, with up to five lightning-caused fires per 100 ha per year (Barrows 1978). Fire season in the GALWC begins as early as April and extends through September. The GALWC is dominated by low-severity (low forest mortality) surface fire regimes with mixed severity regimes found at upper elevations (Swetnam and Dieterich 1985; Abolt 1996). During dry years of the 20th century, fire behavior has been extreme with stand-replacing fire common across all elevations.

At upper elevations, forests of the GALWC comprise mixed stands of Douglas-fir (*Pseudotsuga menziesii*), southwestern white pine (*P. strobiformis*), Englemann spruce (*P. engelmannii*), subalpine fir (*Abies lasiocarpa*), white fir (*A. concolor*), and aspen (*Populus tremuloides*). At middle elevations, ponderosa pine (*P. ponderosa*) stands cover extensive mesas above the west and middle forks of the Gila River. Piñon-oak-juniper woodlands (*P. edulus Englemannii, Juniperus deppeana, J. monosperma*, and *Quercus spp.*) gain dominance as elevation decreases. Piñon-oak-juniper woodlands and ponderosa pine forests make up a large proportion of the GALWC (21% and 23% respectively). Broad valleys at the lowest elevations support desert scrub and grasslands (*Ceanothus, Artemisia*, and *Yucca* spp.)

Selway-Bitterroot Wilderness Complex

The Selway-Bitterroot Wilderness Complex (SBWC) in Idaho and Montana, USA (Figure 1) is a 785,090-ha wilderness area, second in size (in the conterminous United States) only to the adjacent Frank Church River-of-No-Return Wilderness in Idaho. The area is characterized by extremely rugged terrain with broad topographic variation. Portions of the wilderness are found on the Bitterroot, Clearwater, Lolo, and Nez Perce National Forests. The eastern portion of the wilderness consists of the Bitterroot Mountains. These large (3,000 + m), granitic mountains follow the eastern boundary of the wilderness for 70 km and comprise most of the upper subalpine and alpine forest ecosystems of the SBWC. East/west-oriented glacial valleys dissect the mountains to

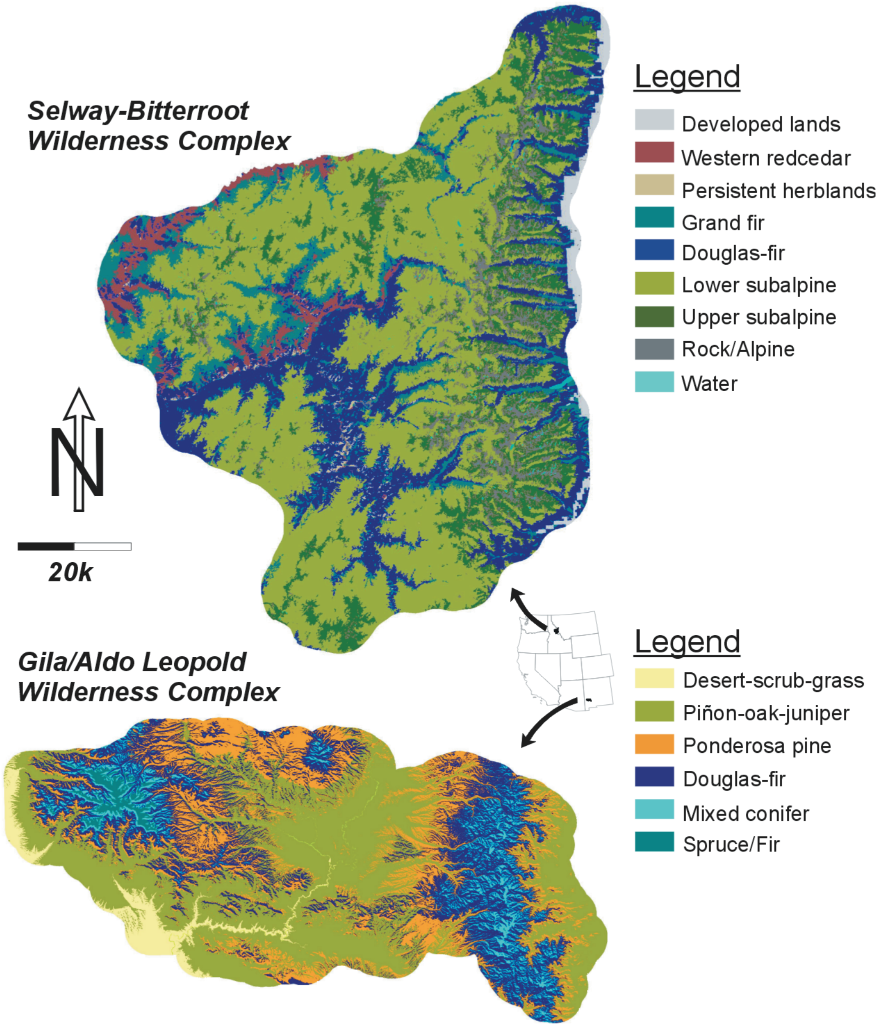

Figure 1. Vegetation for the 486,673 ha Gila/Aldo Leopold and the 785,090 ha Selway-Bitterroot Wilderness Complexes.

valley bottoms as low as 1,000 m. The central/southern portion of the wilderness comprises the majority of the Selway River basin. This area consists of rugged terrain with complex high ridges dissected by steep canyons as low as 500 m. The northwestern portion of the wilderness falls within the Lochsa River drainage with high mountains (the Clearwater Mountains) and forested valleys with over 1,500 m of relief. Mountainous geology of the SBWC is characterized by granitic rock shaped by Pleistocene glaciation. Lower elevations are dominated by substrate formed in a series of volcanic events during the Mesozoic and Cenozoic periods (Greenwood and Morrison 1973). The canyons and valleys of the central Selway and Clearwater River drainages were dissected prior to the eruption of the Columbia River basalt (Habeck 1972).

Average precipitation in the SBWC is higher than the GALWC. Along the main stems of the Lochsa and Selway Rivers close to 1000 mm of precipitation falls annually, with values as high as 1800 mm in the central and Bitterroot mountain ranges; over 50% of this precipitation falls as snow (Finklin 1983). January is usually the wettest month with average monthly precipitation ranging from 75 mm to 250 mm (Finklin 1983). Late summer (July and August) is the driest time of year with average monthly precipitation between 20 and 30 mm. Summertime precipitation varies widely; values have ranged from 7 mm in July 1969 to 160 mm in July 1975 (Finklin 1983). The fire season in the SBWC begins in June and may extend through September. Fire regimes are mixed, with patchy stand-replacement fire dominant in upper elevation forests (70% of the SBWC) and lower severity, surface fire dominant at lower elevations. Stand-replacement fires occur across all elevations during extreme years (Brown et al. 1994; Habeck 1972). Though less frequent than in the GALWC, large thunderstorms occur throughout the spring and summer, with a peak in activity during the early summer. Dry thunderstorms are common in the late summer and early fall. Monthly mean temperatures range from −10 °C in January to 20 °C in July and August.

At elevations around 2,500 m, forests in the central, southern and eastern portions of the SBWC are dominated by subalpine forests containing assemblages of Englemann spruce, subalpine fir, whitebark pine (*P. albicaulis*), and lodgepole pine (*P. contorta*). Stands of lodgepole pine result from widespread fires and are extensive, with relatively homogenous stand structure and ages (Arno et al. 1993). Seventy percent of the SBWC is comprised of subalpine forests with highest subalpine elevations characterized by mixed whitebark pine/alpine larch (*Larix lyallii*) forests (Habeck 1972) and middle elevations characterized by mixed ponderosa pine, Douglas-fir, and western larch (*L. occidentalis*) forests. As elevation decreases these assemblages change to more mesic Douglas-fir/grand fir (*A. grandis*) forests. Diverse, Pacific maritime forests distinguish the lowest elevations, along the main stem of the Lochsa and Selway Rivers, with assemblages of western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), western white pine (*P. monticola*), and Douglas-fir ranging from 500 m to 1,500 m.

Methods

Spatial data

Fire atlases

Twentieth-century fire perimeters were obtained from archival fire data at the Gila National Forest and digitized for the GALWC. For the SBWC, perimeters were obtained in digital form from the Bitterroot, Clearwater, and Nez Perce National Forests. Fire archives consisted of old fire reports or operational fire perimeter maps (Rollins 2000; Rollins et al. 2001). Each annual set of fire perimeters was converted into a grid representing burned and unburned areas. These annual grids were added together to create continuous surfaces of fire frequency for each study area (Figure 2). Again, in this paper we use the term fire frequency to describe the number of times a specific pixel burned during the period of record for each fire atlas. To include fires that burned over the wilderness boundary we 'clipped' the final fire atlases to a 5-km buffer around the wilderness boundary for each study area. This boundary defined the extent of the wilderness complexes for the purpose of our analyses.

Topography

Digital elevation data were obtained from the USDA Forest Service, Rocky Mountain Research Station Fire Sciences Laboratory in Missoula, Montana. Digital elevation data were developed as two compiled sets of USGS 7.5-minute digital elevation models (DEMs, 30 m cells) for the GALWC and SBWC by Keane et al. (1998, 2000). For both areas, a combination of Level 1 and Level 2 DEMs was used to obtain complete coverage of the study area. Level 1 DEMs sometimes show a horizontal banding pattern, and this was the case in some of the DEMs used. An equal weight, directional filter (seven cells high and one cell wide) was applied to the level 1 DEMs to smooth areas where horizontal banding was most apparent. The DEMs were then tiled together, and edges between Level 1 and Level 2 DEMs were filtered to smooth transitions between adjoining datasets (Keane et al. (1998, 2000)). Each DEM was 'clipped' to the extent of the fire atlas. Slope and aspect surfaces were derived from the final DEMs using the Arc/Grid commands 'slope' and 'aspect' (ESRI 1998). We derived an insolation index based on sun angles (elevation and azimuth) calculated for 1900 GMT (12 noon) for the 15th of each month of the fire season for each area (April–September for the GALWC and May–September for the SBWC). Using ENVI (ENvironment for Visualizing Images) image processing software and the DEMs from each area, the data from each month were averaged to yield a single surface for each study area integrating slope, aspect and geographic location and representing relative amounts of insolation across the landscape.

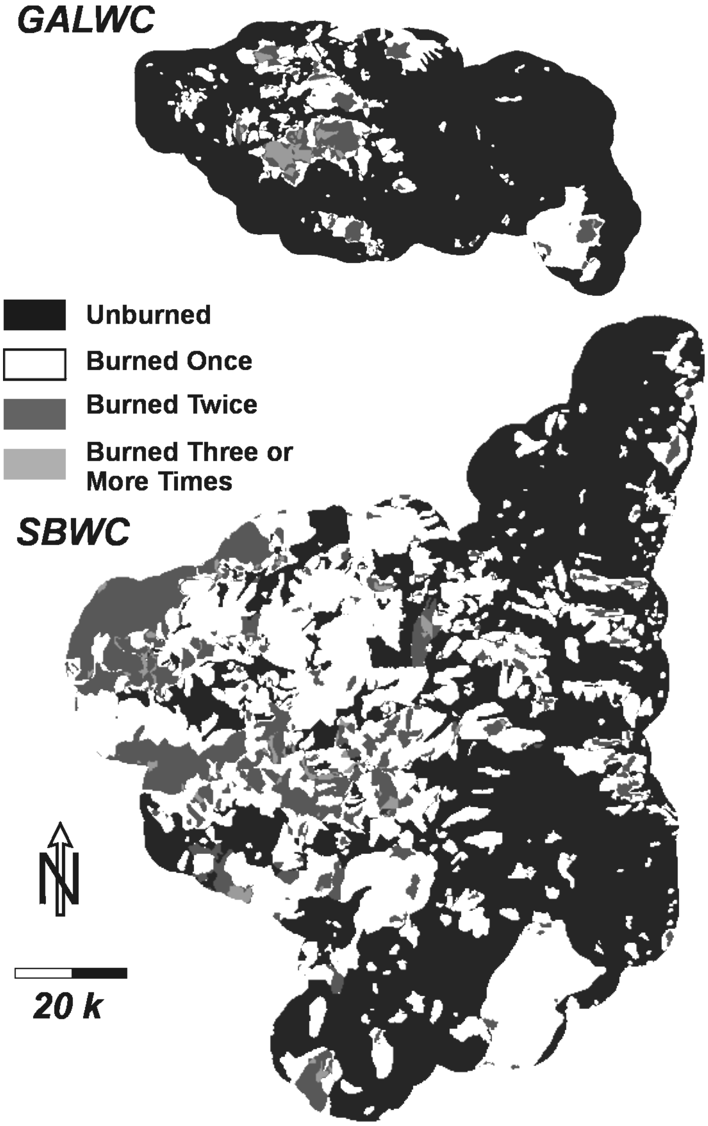

Figure 2. Reburned areas in each wilderness area based on archives of 20th century fire perimeters. Data extend from 1909 to 1993 in the GALWC and from 1880 to 1996 in the SBWC.

Potential vegetation

We used potential vegetation type (PVT) to describe biophysical settings in each wilderness area (Keane et al. (1998, 1999, 2000)). Potential vegetation types represent aggregated habitat types and were named for the late successional community presumed to exist for a specific site in the absence of disturbance (Daubenmire 1968a; Pfister and Arno 1980; Cooper et al. 1991). We used PVTs, as opposed to finer-grained habitat types because the relatively coarse resolution of PVT maps more closely matched the minimum mapping unit of the digital fire atlases. Potential vegetation types have been used to describe distributions of plant habitats across broad landscapes for Rocky Mountain forests (Daubenmire 1968b; Pfister and Arno 1980; Keane et al. 1999). Though originally based on single-pathway succession (Daubenmire 1968a), PVTs remain valid for multiple-pathway succession systems (Cooper et al. 1991). Vegetation communities rarely reach late successional stages because of recurring disturbances and non-linear successional trajectories (Noble and Slayter 1980; Cooper et al. 1991), but indicator species are usually present even in disturbed areas.

Classifications of PVTs were developed from models incorporating geographic location, field data, topography, local productivity, and soil characteristics. With these data, area ecologists and local scientists formulated series of rules to assign PVT to different permutations of location and topographic classifications for each wilderness complex (Keane et al. (1998, 2000)). These rules were then implemented as a spatial model within a GIS. Thematic accuracies of these layers were determined by comparison with field data by Keane et al. (1998, 2000). Overall accuracies of PVT maps were 65% in the SBWC (Khat 0.57) and 89% in the GALWC (Khat 0.45; Keane et al. (1998, 2000)). We excluded areas of development, riparian forests, and water bodies from our analyses. It is important to note that although PVTs were named for the late successional tree species presumed to occupy a given site, and are meant to represent biophysical conditions, the PVT classifications used for each wilderness area also represented the distribution of dominant existing forest types in each wilderness complex.

Climate data

Estimates of summer Palmer Drought Severity Index (PDSI) were available for the 20th century from the National Oceanic and Atmospheric Administration National Climatic Data Center in Boulder, Colorado (http://www.ncdc.noaa.gov/ol/climate/climatedata.html). PDSI is a measure of prolonged (monthly and yearly) periods of water status and accounts for precipitation, evapotranspiration, and soil moisture conditions (Palmer 1965). Typical values range from negative 6 (drought) to positive 6 (moist conditions). Data were summarized within state by climate divisions. For each wilderness complex we used April through October PDSI to represent drought status during the months when fires were most likely to occur.

Data analysis procedures

Using digital fire atlases we document unburned area and areas burned once, twice, and three or more times for each wilderness complex, by PVT. Percentages were calculated as the proportion of the total area of each PVT in each fire frequency class. In the SBWC, subalpine forests were divided into lower subalpine dry and moist and upper subalpine dry and moist to examine differences between fire frequencies on dry versus moist subalpine sites in the SBWC and to facilitate comparison with the mixed conifer and spruce/fir PVTs in the GALWC.

We used a graphical/statistical approach to assess relationships between fire frequency and topography, vegetation, and climate. Maps of 20th century fire frequency were cross-tabulated with data for elevation, slope, aspect, insolation index, and PVT to derive distributions of fire frequency over landscape variables. Distributions of landscape variables (i.e. topography and vegetation) within each fire frequency class (unburned, burned once, burned twice, and burned three or more times) were compared with distributions of the landscape variables over the entire study area to test for random conditions. We derived proportions of area burned in each fire frequency class for each landscape variable to enable direct comparison on identical scales, despite uneven distribution of area burned in different fire frequency classes. Despite conversion to proportions, our use of the term fire frequency remains the same, except we now refer to the *proportion* of pixels in a given landscape variable that burned a specific number of times. Cumulative distributions of proportions were compared using two sample Kolmogorov-Smirnov tests (KS-tests) for differences in empirically derived, continuous distributions (H_o: distributions are not different, $P > 0.10$). For discrete distributions of PVT and aspect in each wilderness complex we used log-likelihood tests for goodness-of-fit (*G*-tests) to assess differences between observed and expected proportional areas in different fire frequency classes (H_o: distributions are not different, $P > 0.10$).

We used superposed epoch analysis (SEA, Lough and Fritts (1987) and Swetnam (1993), Grissino-Mayer and Swetnam (2000)) to determine whether periods of drought or moist conditions were related to years with large areas burned. Superposed epoch analysis has been used to evaluate the influence of climate conditions prior to and during years with extensive fires at landscape to regional scales (Swetnam 1993; Swetnam and Betancourt 1998; Veblen et al. 1999). In this study, we used SEA to analyze climate prior to and during the 8 years with the largest areas burned in each wilderness complex. We excluded 1992 and 1993 from SEA in the GALWC as large fires during these years were managed as prescribed natural fires and were allowed to reach large sizes due to relatively wet conditions (Garcia 1997). We conducted separate SEA on ponderosa pine and Douglas-fir (GALWC), mixed conifer and spruce/fir (GALWC), Douglas-fir (SBWC), and subalpine (SBWC)

Table 1. Area burned (ha) and percent of potential vegetation type (PVT) burned by fire frequency class for the entire study area and PVTs within each wilderness complex. The majority of each wilderness complex remained unburned in the 20th century. Reported areas exclude developed lands, riparian forests, and water.

	Gila/Aldo Leopold Wilderness Complex									
	Unburned		Once		Twice		Three or more times		Total	
	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
Entire study Area	383,286	79	72,580	15	23,038	5	7,020	1	485,924	100
Desert/grass	19,611	100	94	0	6	0	0	0	19,711	4
Piñon/oak/Juniper	185,565	88	17,860	8	5,831	3	1,089	0	210,345	43
Ponderosa pine	71,686	71	19,700	19	7,292	7	2,596	3	101,275	21
Douglas-fir	76,358	67	25,949	23	8,401	7	3,131	3	113,841	23
Mixed conifer	23,989	72	7,905	23	1,476	4	204	1	33,574	7
Spruce/fir	6,077	85	1,072	15	32	0	0	0	7,181	2

	Selway-Bitterroot Wilderness Complex									
	Unburned		Once		Twice		Three or more times		Total	
	Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
Entire study Area	398,049	52	275,775	36	87,028	11	7,379	1	768,230	100
Western redcedar	3,361	13	10,076	38	12,409	47	766	3	26,612	3
Persistent herblands	1,504	31	2,292	46	937	19	190	4	4,923	1
Grand fir	28,668	37	28,946	37	19,423	25	1,213	2	78,250	10
Douglas-fir	63,832	49	44,631	35	18,433	14	2,351	2	129,247	17
Lower subalpine	195,627	52	144,738	39	31,568	8	2,523	1	374,456	49
Upper subalpine	67,723	67	31,480	31	2,354	2	160	0	101,718	13
Rock/Alpine	37,333	70	13,606	26	1,904	4	177	0	53,025	7

forest PVTs to assess drought relationships within similar biophysical settings between study areas.

Results

Archival mapped fire perimeters extended from 1909 to 1993 in the GALWC and from 1880 to 1996 in the SBWC (Rollins 2000; Rollins et al. 2001). Mapped data indicated that 139,716 ha burned in 220 fires in the GALWC and 472,921 ha burned in 524 fires in the SBWC. In the GALWC, 7,021 ha burned three or more times; 5,727 ha (82%) of this were in ponderosa pine and Douglas-fir PVTs, which make up 44% of the study area (Table 1). In the SBWC, 7,379 ha burned three or more times, with the majority of reburned areas in Douglas-fir and lower subalpine PVTs (Table 1). More area burned multiple times in lower than in upper subalpine forest PVTs. While slightly higher proportions of moist subalpine forests burned once and twice, overall, xeric subalpine PVTs accounted for the majority of area in subalpine forests burned more than once in the 20th century (Table 2).

Ponderosa pine and Douglas-fir PVTs had the highest proportions burned in each study area. More area burned in these PVTs than expected if burn patterns were random (Figure 3). The piñon/oak/juniper PVT in the GALWC and the lower subalpine PVT in the SBWC burned less often than expected if burned areas were randomly distributed across the study areas. Large areas that burned multiple times in ponderosa pine and Douglas-fir PVTs in the GALWC and western redcedar and Douglas-fir PVTs in the SBWC contributed most to the overall significance of log-likelihood tests.

Areas burned multiple times in the GALWC were found at higher elevations than expected based on the distribution of elevation for the entire area (Figure 4). The majority of areas burned three or more times in the GALWC were found between 2,300 m and 2,600 m. Mean elevation in the GALWC was 2,200 m. Two-sample KS-tests for differences in distributions showed significant differences between the distribu-

Table 2. Area burned (ha) and percent of PVT burned in each fire frequency class for subalpine PVTs in the SBWC. Dryer subalpine forests burned more frequently.

	Selway-Bitterroot Wilderness Complex — Subalpine Forests									
	Unburned		Once		Twice		Three or More Times			Total
	Ha	%	Ha	%	Ha	%	Ha	%	Ha	% Subalpine Forests
All Subalpine Forests	263,391	55	176,062	37	34,069	7	2,684	1	476,208	100
Lower Subalpine Moist	73,672	49	60,388	41	14,139	9	797	1	148,967	31
Lower Subalpine Dry	121,998	54	84,188	37	17,575	8	1,727	1	225,489	48
Upper Subalpine Moist	28,427	66	13,832	32	1,062	2	22	0	43,343	9
Upper Subalpine Dry	39,293	67	17,653	30	1,292	2	138	0	58,377	12

tion of elevation for all fire frequency classes (excluding unburned) and the distribution of elevation for both wilderness areas ($P < 0.10$, Table 3). Areas burned multiple times in the SBWC were found between 1,000 m and 1,700 m (Figure 4). Mean elevation in the SBWC was 1,758 m. KS-tests indicated no significant differences between distributions of slope for areas with different fire frequencies in either study area (Table 3). Log-likelihood analyses indicated that northeastern aspects in the GALWC and western and southwestern aspects in the SBWC have higher fire frequencies than expected under random conditions ($P < 0.10$, Figure 5).

In the GALWC, cumulative distributions of insolation index for areas that burned three or more times were significantly different from the distribution of insolation across the entire area ($P < 0.05$, Table 3). In general, areas burned three or more times had lower insolation values (Figure 6). There were no significant differences between insolation index for other fire frequencies in the GALWC, and we found no difference between distributions of insolation for different fire frequency classes in the SBWC.

Annual area burned was compared to drought status using superposed epoch analysis. In the GALWC current or lagged year drought status were not related to years with large areas burned (Figure 7). When partitioned by PVT, SEA indicated that years in which large areas burned in the upper elevation mixed conifer and spruce-fir PVTs of the GALWC were significantly drier than average ($P < 0.01$). In the SBWC, years with extensive fires were significantly dry ($P < 0.01$). This pattern remained the same when SEA was performed separately for Douglas-fir and Subalpine forests (Figure 7).

Discussion

Spatial distributions of fire frequency during the 20th century are related to gradients of landscape variables and climate in each wilderness complex. Relationships between landscape characteristics and areas burned multiple times showed key differences and similarities between the two wilderness complexes. These unique and general patterns highlight important aspects of fire regimes for the forests of the Northern and Southern Rocky Mountains.

Two main limitations for using fire atlases to study the landscape controls over fire frequency over broad areas and for long periods of time are:

1. database quality and
2. anthropogenic effects on the size and frequency of fires

It was impossible to completely assess the spatial accuracy of these historical spatial data. Fire mapping methods change over time in archived sets of fire perimeters, resulting in an uneven temporal distribution of precision and accuracy. For the most part, fires that had important financial, ecological, or social significance tend to be mapped and archived (McKelvey and Busse 1996). This may bias the data toward large, high severity events. The degree of this bias is unclear and probably varies through time. However, the mapped fires likely represent a large proportion of the area actually burned (Strauss et al. 1989). Comparison with the National Interagency Fire Management Integrated Database (USDA Forest Service. 1993) suggested that less than 1% of fires less than 50 ha were accounted for in the mapped perimeter data. On the other hand over 95% of fires over 1,000 ha were included.

Fire atlases used in these analyses lacked information describing fire severity patterns or unburned ar-

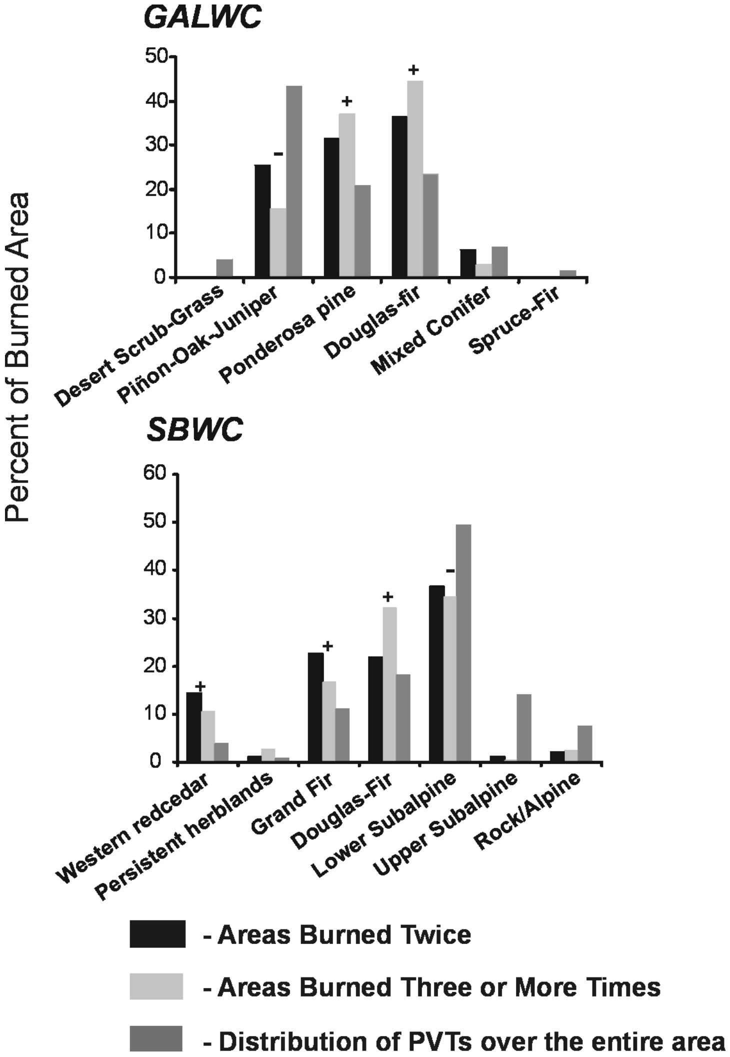

Figure 3. Areas burned two or more times for different potential vegetation types. A plus (+) indicates a significant positive difference and a minus (–) a significant negative difference ($P < 0.10$) between the spatial distribution of area burned multiple times in different PVTs and the distribution of PVT over the entire wilderness complex.

eas within fire perimeters. Fire atlases with broad temporal extents typically do not contain this information. Care must be taken to incorporate existing knowledge of general fire regimes in the study area (e.g. from dendroecological analysis) when making inferences based on fire atlases that contain no information on severity. Fire atlases from the GALWC and the SBWC also contained no information about different levels of fire suppression imposed on the spatial patterns of mapped fires. By conducting this research in wilderness areas, the effects of anthropogenic fire exclusion were reduced relative to areas with extensive road networks or land-use patterns. Fires in these areas, while suppressed, were not subject to the same degree of mechanical manipulation as fires in adjacent 'managed' landscapes. That is, there were no extensive areas of fireline construction using mechanical equipment. For the most part, the effect of fire suppression was more of a matter of fire exclusion. That is, fires that may have reached large sizes were extinguished at an early stage by aggressive initial attack by aerially delivered firefighters and/or aerial retardant operations. However, fire suppression effects may have obscured some landscape-fire frequency relationships to the degree that our interpretations of landscape fire relationships were tenuous.

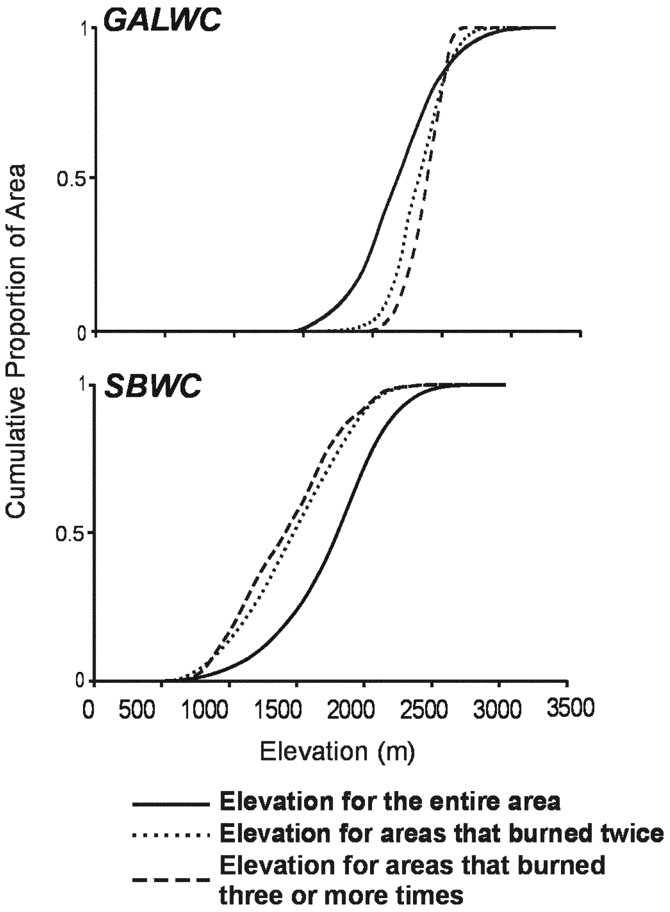

Figure 4. Cumulative distributions of elevation for areas burned multiple times and the distribution of elevation over each wilderness complex. Distributions are plotted as proportions to equalize scales. Shifts in the distributions of elevation for areas burned multiple times indicate higher fire frequencies in high elevations in the GALWC and low elevations in the SBWC. The differences in distributions between the two study areas are related to differences in gradients of fuel moisture status and fuel continuity. Two-sided Kolmogorov-Smirnov tests indicated that distributions of elevation for areas burned multiple times were significantly different from elevation over the entire area (P < 0.10).

Table 3. Probabilities for the two-sided Kolmogorov-Smirnov tests for differences in distributions of different fire frequencies and landscape variables over the entire study area. Results are reported for the entire period of record. Significant differences (P < 0.10) are shown in bold.

	GALWC			*SBWC*		
	Elevation	Slope	Insol. Index	Elevation	Slope	Insol. Index
Unburned	0.43	1.00	1.00	0.00	0.97	1.00
Once	**0.00**	1.00	0.99	**0.00**	0.97	1.00
Twice	**0.00**	0.99	0.77	**0.00**	0.30	1.00
Three or more Times	**0.00**	0.13	**0.04**	**0.00**	0.22	0.48

Our results were quite similar to findings of other studies that used fire history information to investigate landscape-fire relationships (Barton 1994; McKelvey and Busse 1996; Kushla and Ripple 1997). Further, 20th century relationships between topography, vegetation, and climate in the GALWC and SBWC are similar to results from previous research in other areas using pre-20th century fire history databases (Romme and Knight 1981; Martin's 1982; Engelmark 1987; Brown et al. 1994; Barton 1994; Heyerdahl et al. 2001). This supports the assertion that patterns revealed by analyses of 20th century fire patterns were also the major controls over that governed the spatial patterns of burning prior to anthropogenic manipulation of wildland fire patterns.

Despite limitations, empirical analyses of landscape-fire relationships using digital fire atlases provide useful information for evaluating the factors that control fire regimes at landscape to regional scales. The fire atlases used here have both broad temporal and spatial extents which makes them invaluable for evaluating the causal agents of fire patterns at landscape scales. Fire atlases represent a useful source of fire history information and allow spatial analyses of fire location, fire size distribution, and analyses of recent fire frequency. These analyses are often lacking from fire history research based on fire-scarred trees (Morgan et al. 2001; Rollins et al. 2001).

Landscape variables

The piñon/juniper PVT in the GALWC and the lower subalpine forest PVT in the SBWC re-burned significantly less often than expected relative to the distribution of these types over the entire study area (Table 1, Figure 3). This could suggest that these areas had been more affected by fire exclusion than other vegetation types. However, the temporal extent of our fire atlases may have been too short to represent the long fire return intervals (i.e. low fire frequency) previously described for these forests (Swetnam and Dieterich 1985; Abolt 1996; Barrett and Arno 1991; Brown et al. 1994). Throughout the 20th century, fire frequencies in the GALWC and SBWC were low compared to reconstructions of pre-20th century fire regimes (Swetnam and Dieterich 1985; Barrett and Arno 1991; Brown et al. 1994; Abolt 1996). This is likely due to reduction of fine fuels because of extensive grazing in the GALWC (Swetnam and Dieterich 1985; Savage and Swetnam 1990) and aggressive suppression of fires in both the GALWC and SBWC (Gruell et al. 1982; Brown et al. 1994; Covington et al. 1994; Swetnam and Baisan 1996). Elevation ranges corresponding with areas burned multiple times were different in each wilderness complex (Figure 4); however, the ponderosa pine/Douglas-fir PVTs found at these different elevations are quite similar with regard to dominant overstory tree species. Understories are similar with a larger shrub component in the Douglas-fir PVT in the SBWC. Previous research based on pre-20th century fire history data suggests that Douglas-fir and ponderosa PVTs in each wilderness complex are the most similar with regard to fire frequency (Swetnam and Dieterich 1985; Barrett and Arno 1991; Brown et al. 1994; Abolt 1996).

Douglas-fir and ponderosa pine PVTs are found at low to moderate elevations in each wilderness complex and are characterized by conditions that are dry relative to higher elevations. Prior to European settlement in the Western United States, ponderosa pine and Douglas-fir PVTs were characterized by open stand structures maintained by frequent low-to-moderate severity surface fires that created patchy stand age and size distributions (Weaver 1951; Cooper 1961; Arno (1976, 1980); Gruell et al. 1982; Swetnam and Dieterich 1985). Fine fuel loads, fuel structure and continuity, and local topography dominate fire behavior in these stands. During the latter part of the 20th century, stand-replacing fires have occurred in some areas where closed-canopy conditions developed during the fire suppression era (Gruell et al. 1982; Agee 1993; Covington and Moore 1994). In 1975 both wilderness areas implemented prescribed natural fire management programs (currently referred to as wildland fire use) as part of efforts to restore fire as a keystone disturbance process (Garcia et al. 1978; Frost 1982). These efforts have increased the amount of fire in each wilderness complex, but some PVTs have been affected more than others (Brown et al. 1994; Rollins et al. 2001). In the GALWC, 68% of PNF-era area burned was in ponderosa pine and Douglas-fir PVTs. In the SBWC, 71% of the area burned after 1975 was in ponderosa pine and Douglas-fir forests.

Although areas that burned multiple times appeared, graphically, to occur on steeper slopes in both wilderness complexes, there was no statistically significant relationship evident. Slope is an important determinant of fire behavior and subsequent fire effects (Agee 1993; Rothermel 1983; Albini 1976). Engelmark (1987) found higher fire frequencies on steeper slopes in northern Sweden. In addition to more efficient heat transfer to upslope fuels via convection (Agee 1993), higher fire frequencies on steeper slopes may result from a ‘chimney’ effect based on landform (Swanson 1981) or from lower soil moistures on steeper slopes (Brown 1972). Apparently, these effects are important at local scales (e.g. first-order watersheds) and may not be as evident at the landscape scales analyzed here for the GALWC and SBWC. The coarse resolution of the fire atlases may account for the lack of significant differences in fire frequencies relative to slope, as many of the more subtle relationships between topography and fire

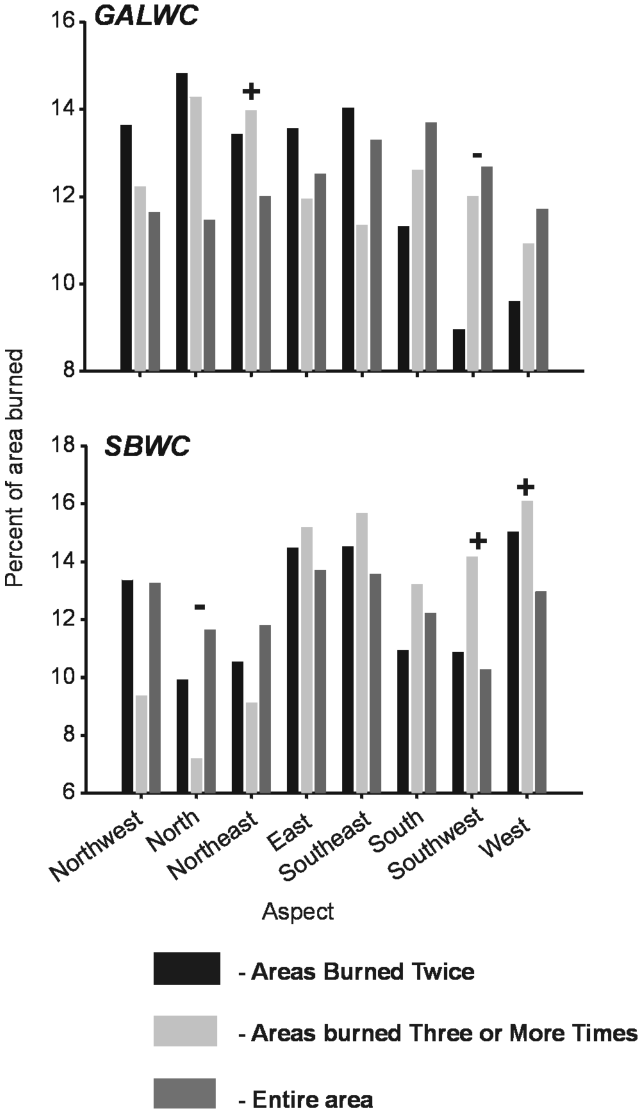

Figure 5. Aspect for different fire frequencies and aspect over the entire area in each wilderness complex. Chi-square tests indicated significant differences in distributions, with inverse aspect-fire frequency relationships between the GALWC and SBWC. + indicates a significant positive difference and – a significant negative difference ($P < 0.05$) between the distribution of area burned multiple times in different aspect classes and the distribution of aspect over the entire wilderness complex.

spread are not captured by relatively coarse spatial fire perimeter data used in this study.

Relationships between aspect and fire frequency were nearly opposite between the GALWC and SBWC (Figure 5). This 'mirror image' in the relationship between aspect and fire frequency highlights important differences in fire regime characteristics in each area. Fires in the GALWC burn, in general, with low-to-moderate severities (i.e. low tree mortality and fire intensity). In this semi-arid landscape, fires are often constrained by the amount and horizontal continuity of fuel. Northern and northeastern aspects are more productive, leading to higher herbaceous fuel continuity, and thus, a higher probability of re-burn. Fires in the Southwestern United States become much more infrequent and intense as forests transition to more mesic and dense mixed conifer and spruce/fir forests (Baisan and Swetnam 1990; Grissino-Mayer et al. 1995; Swetnam and Baisan 1996; Abolt 1996), but these forests represent only 9% of the GALWC.

In contrast, fire regimes in the SBWC are characterized by infrequent moderate-to-high severity fires that kill a large proportion of trees (Barrett and Arno 1991; Brown et al. 1994). These fire regimes occur in subalpine forests (70% of the SBWC) and moist grand fir and western redcedar PVTs. Widespread fires in subalpine forests are constrained by the availability and moisture status of large, woody fuels. Southern and southwestern aspects receive more direct insolation, causing desiccation and preheating of fuels (Agee 1993). High insolation and xeric conditions on south-facing slopes may slow vegetation regrowth following severe burns.

Climate-fire frequency

In the GALWC, areas that burned three or more times experienced significantly lower insolation than those that burned less often or not at all (Figure 6). This supports assertions that northern-facing slopes in the GALWC re-burn more frequently because of higher productivity leading to more biomass to fuel fires. In the GALWC, areas with the highest insolation (i.e. steep south-facing slopes) are likely to have low fine fuel continuity because the extremely dry conditions limit biomass production. No significant differences were found in the distribution of insolation for areas with different fire frequencies in the SBWC (Table 3). Some 72% of the area burned in the SBWC burned in very large (>20,000 ha) fires prior to 1935. These fires were strongly related to summer drought and burned primarily in dense, low-elevation forests (Moore 1996; Larsen and Delaven 1922). Large, dead fuels accounted for most areas that re-burned in the early 20th century in low elevation, mesic forest types (Larsen and Delaven 1922). In these situations, local topography plays a smaller role than wind and antecedent moisture conditions in constraining fire patterns.

Years with extensive fire in the GALWC and SBWC corresponded with regional April–October drought. In the GALWC, large high elevation fires in the 1940s and 1950s corresponded with the most intense, sustained drought since 1580 (Swetnam and Betancourt 1998). Years with extensive fire years tended to be much drier in the SBWA than the GALWC (Figure 7). This supports the assertion that fuel continuity, rather than fuel moisture, is a main constraint on fire frequency in the GALWC. Widespread fire years corresponded with significantly dry years in the mixed conifer and spruce/fir PVTs in the GALWC and all PVTs in the SBWC (Figure 7). This suggests that fire regimes in upper elevation forests of the GALWC are similar to fire regimes of the SBWC. That is, fires in upper elevation forests of the GALWC are probably limited by fuel moisture as opposed to fuel continuity as in the PVTs dominant at lower elevations of the GALWC.

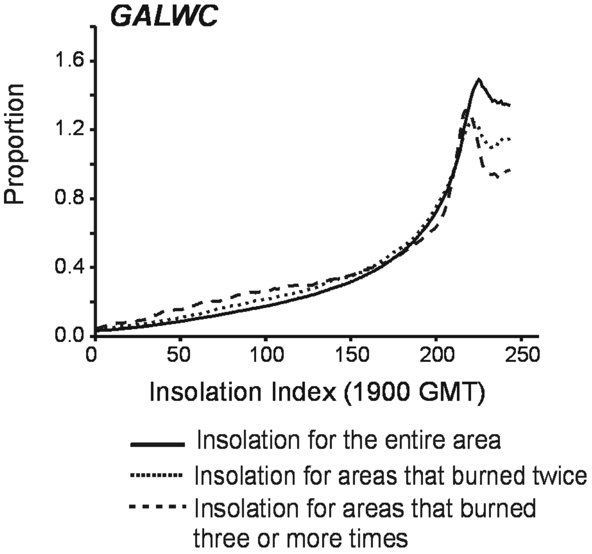

Figure 6. Insolation index for different fire frequency classes and over the entire GALWC. Insolation index was calculated from sun angles determined using ENVI image processing software and range from 0 (low insolation) to 255 (high insolation). Lower values of insolation had proportionately higher fire frequencies than areas with high insolation.

Regional climate and annual area burned are strongly related in the Southwestern United States. The strength of this regional-scale forcing of fire regimes is related to El Niño Southern Oscillation (ENSO) precipitation events (Swetnam and Betancourt (1990, 1998)). Our results were not entirely consistent with the findings of Swetnam and Betancourt (1998). Using long time series of fire and climate data from a network of tree-ring fire history reconstructions in the Southwestern United States, Swetnam and Betancourt (1998) show that widespread fires in the Southwestern United States tended to occur during a dry year preceded by one to three wet years and that fire regimes in ponderosa pine forests of the Southern Rocky Mountains are constrained by fine fuel amount and continuity as much as by fuel moisture.

Barrett et al. (1997) found no relationship between regional drought and multi-year 'fire episodes' (i.e. 5-year intervals with high fire occurrence), attributing high fire frequencies instead to inter-regional weather variations (e.g. intense, local storms), mass lightning

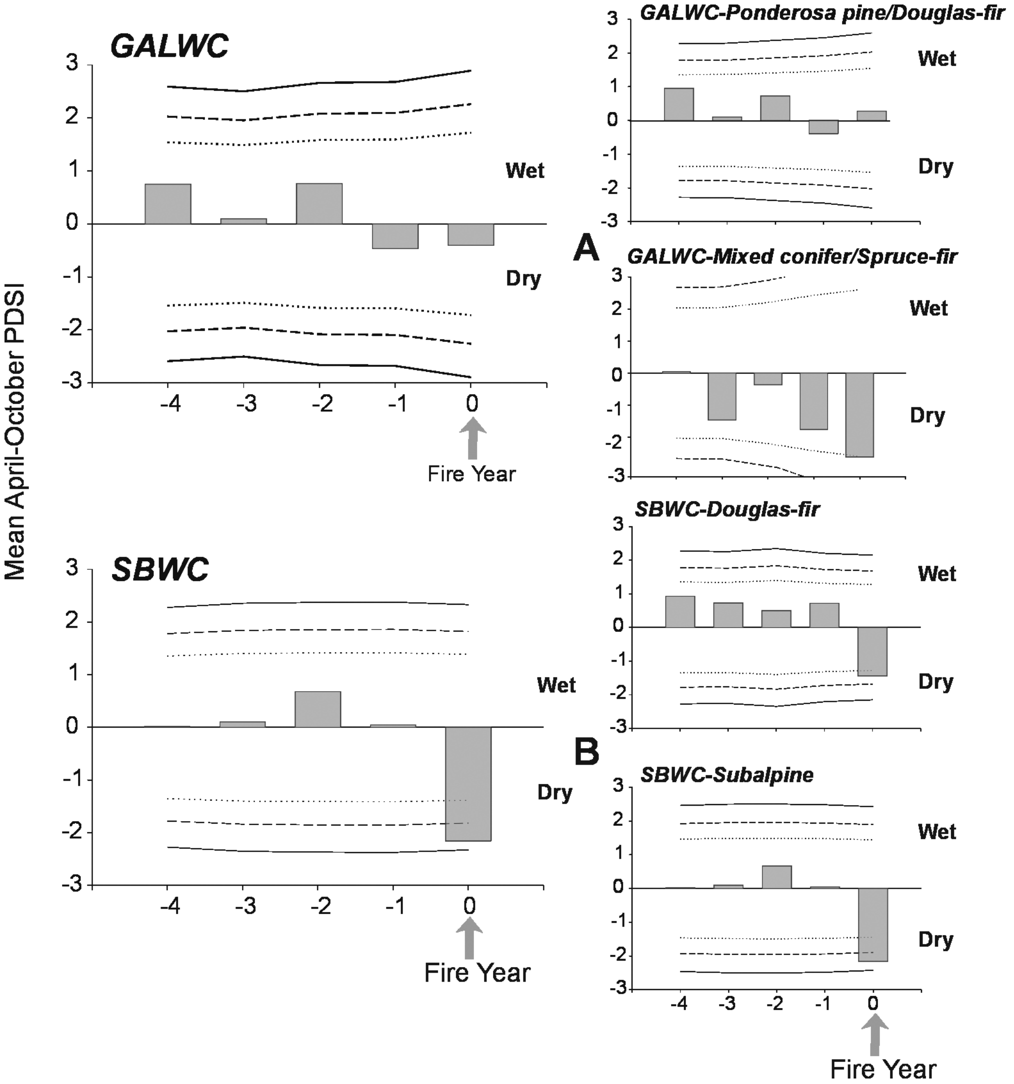

Figure 7. Results from superposed epoch analysis (SEA) in each wilderness complex and A) SEA for ponderosa-pine/Douglas-fir and mixed conifer/spruce/fir PVTs in the GALWC and B) SEA for Douglas-fir (includes seral ponderosa pine) and subalpine PVTs in the SBWC. Bars indicate mean April-October PDSI values for the eight largest fire years (year 0) and during four lagged years. The solid, dashed, and dotted lines indicate 99.9, 95, and 90 percent confidence intervals, respectively, based on Monte Carlo simulation. Large fire years corresponded with significantly dry years in the SBWC and in the mixed-conifer PVT in the GALWC.

ignitions, and strong local winds created from widespread fire events. However, lack of annual precision in Barrett's reconstructed fire episodes and use of climate reconstructions from Oregon rather than the more regionally appropriate reconstructions for the Northern Rockies (e.g. Cook et al. (1999)) may have contributed to the overall lack of significant correspondence between large fire years and drought indices.

Drought years in the GALWC occurred on normal to wet years in the SBWC and vice versa. Precipitation variability over the Western United States has been shown to pivot near 40° N on time scales from decades to centuries (Dettinger et al. 1998). When conditions are wet in northern states, conditions tend to be dry in southern states and vice versa (Dettinger et al. 1998; McCabe and Dettinger 1999). This pivot in precipitation is especially pronounced during El Niño Southern Oscillation (ENSO) events, which entrain fire regimes throughout the Southwestern United States (Swetnam and Betancourt (1990, 1998); Dettinger et al. 1998; McCabe and Dettinger 1999). This relationship is graphically evident in PDSI and area burned from each area. For example, dry years with large areas burned in the GALWC often correspond with normal or wet periods with less area burned in the SBWC (e.g. 1909, 1913, 1951) and vice versa (e.g. 1919, 1979, and 1988). Improved predictability of ENSO events, along with cross-dated, dendroecological analyses of synoptic fire-drought relationships, may provide a powerful predictive tool for determining the timing and effects of predicted climate change on fire regimes. Because ENSO events can be identified as they develop, such a tool will also be useful in strategic planning for fire suppression during upcoming dry years and management of lightning and human ignited fires in other years.

Conclusions

In summary, our interpretations of the observed patterns are as follows. The amounts and horizontal continuity of surface fuel appear to be the most important factors leading to high fire frequencies in the GALWC. This leads to high fire frequencies on relatively productive sites. In the SBWC, the moisture content of large fuels and tree crowns appears to be most important in influencing the spatial distribution of fire frequency in the area, leading to higher fire frequencies on dryer sites. Past research has evaluated variability in fire behavior at fine spatial and temporal scales (Kushla and Ripple 1997; Finney 1998; Perry 1998) and how fire frequency varies across regions and centuries (Arno 1980; Rothermel 1983; Swetnam and Baisan 1996). By evaluating the spatial and temporal variability of fire frequency at intermediate spatial and temporal scales our results provide a bridge between fine-scale and broad-scale understanding of factors that determine fire regimes of the forests of the Rocky Mountains.

This research demonstrates the utility of using historical fire perimeter data to examine fire-landscape-climate interactions over space and time. The comparative nature of our research strengthens inferences about causal relationships between landscape attributes and fire patterns, providing additional validity to the extrapolation of results from this research to other areas. Our results provide baseline empirical information for implementing existing mechanistic models of landscape change in research focused on how landscape patterns and processes change under different climate and disturbance regimes.

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